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# Experimental Data Analysis of the Vortex Structures in the Wakes of Flapping Wings

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## Abstract

The objective of this paper is to compare the existing methods and develop novel approaches for the experimental data analysis of the unsteady aerodynamics of the flapping wing microaerial-vehicle. These methods are developed for the purpose of identification of the beneficial dynamics and for the development of reduced order models for control design. We first employ Proper Orthogonal Decomposition (POD) method for the data analysis of the PIV measurements in the wakes of piezoelectric flapping wings. The basic idea behind POD based data analysis method is to decompose the time series snapshots of PIV measurements into high energy, POD, modes. The POD modes obtained from the PIV measurement data with different control inputs, such as flapping amplitude, angle of attack and flight speed, are compared to identify high energy modes that are invariant across the range of operating conditions. Similarly the modes that are responsible for maximum energy transfer between the control inputs and the desired output such as lift and thrust are identified. The second method that we propose for the PIV data analysis is inspired from our recent work to develop a novel approach for the spectral analysis of the nonlinear flows. This new method is based on the spectral analysis of the linear transfer operator, the so called Koopman operator, associated with any nonlinear flows. The motivation for this work comes from the desire to perform frequency-based decomposition of the snapshot data as opposed to energy based decomposition in the POD method. While POD-based data analysis method captures all high energy content modes, it ignores the low energy content modes. These low energy modes might play an important role from the dynamics point of view and hence cannot be ignored. We perform the spectral analysis of the linear transfer, Perron-Frobenius (P-F) operator, which is dual to the Koopman operator to obtain the frequency based decomposition of the time series snapshot data. The basic idea behind this approach is to construct the finite dimensional approximation of the linear transfer (P-F) operator that best describes the time evolution of the snapshots data. The eigenvalues and eigenvectors of this transfer operator carry useful information about the system dynamics.

## Disciplines

Aerodynamics and Fluid Mechanics | Aeronautical Vehicles | Aerospace Engineering | Electrical and Computer Engineering

## Comments

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# Experimental Data Analysis of the Vortex Structures in the Wakes of Flapping Wings

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## I. Introduction

THE objective of this paper is to compare the existing methods and develop novel approaches for the experimental data analysis of the unsteady aerodynamics of the flapping wing microaerial-vehicle. These methods are developed for the purpose of identification of the beneficial dynamics and for the development of reduced order models for control design. We first employ Proper Orthogonal Decomposition (POD) method for the data analysis of the PIV measurements in the wakes of piezoelectric flapping wings. The basic idea behind POD based data analysis method is to decompose the time series snapshots of PIV measurements into high energy, POD, modes. The POD modes obtained from the PIV measurement data with different control inputs, such as flapping amplitude, angle of attack and flight speed, are compared to identify high energy modes that are invariant across the range of operating conditions. Similarly the modes that are responsible for maximum energy transfer between the control inputs and the desired output such as lift and thrust are identified.

The second method that we propose for the PIV data analysis is inspired from our recent work to develop a novel approach for the spectral analysis of the nonlinear flows. This new method is based on the spectral analysis of the linear transfer operator, the so called Koopman operator, associated with any nonlinear flows. The motivation for this work comes from the desire to perform frequency-based decomposition of the snapshot data as opposed to energy based decomposition in the POD method. While POD-based data analysis method captures all high energy content modes, it ignores the low energy content modes. These low energy modes might play an important role from the dynamics point of view and hence cannot be ignored. We perform the spectral analysis of the linear transfer, Perron-Frobenius (P-F) operator, which is dual to the Koopman operator to obtain the frequency based decomposition of the time series snapshot data. The basic idea behind this approach is to construct the finite dimensional approximation of the linear transfer (P-F) operator that best describes the time evolution of the snapshots data. The eigenvalues and eigenvectors of this transfer operator carry useful information about the system dynamics.

## II. Experimental Setup of Flapping Wings

The experimental study was conducted in a closed-circuit low-speed wind tunnel located in the Aerospace Engineering Department of Iowa State University. The tunnel has a test section with a  $1.0 \times 1.0$  ft ( $30 \times 30$  cm) cross section and the walls of the test section are optically transparent. The tunnel has a contraction section upstream of the test section with honeycombs, screen structures and a cooling system installed ahead of the contraction section to provide uniform low turbulent incoming flow into the test section.

Figure 1 shows the schematic of the piezoelectric flapping wing used in the present study. The tested piezoelectric flapping wing has a rectangular planform with the chord length 12.7mm (i.e.,  $c=12.7$ mm), wingspan 34mm (i.e.  $b=34$ mm), and thickness 0.26mm. In the present study, the velocity of the incoming flow was set as  $U_\infty = 1.40$  m/s, which corresponds to a chord Reynolds number of  $Re_C = 1,200$ . The turbulence intensity of the incoming flow was found to be about 1.0%, measured by using a hot-wire anemometer.

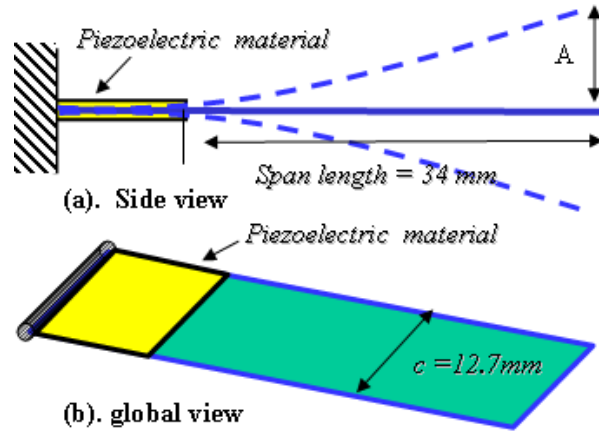
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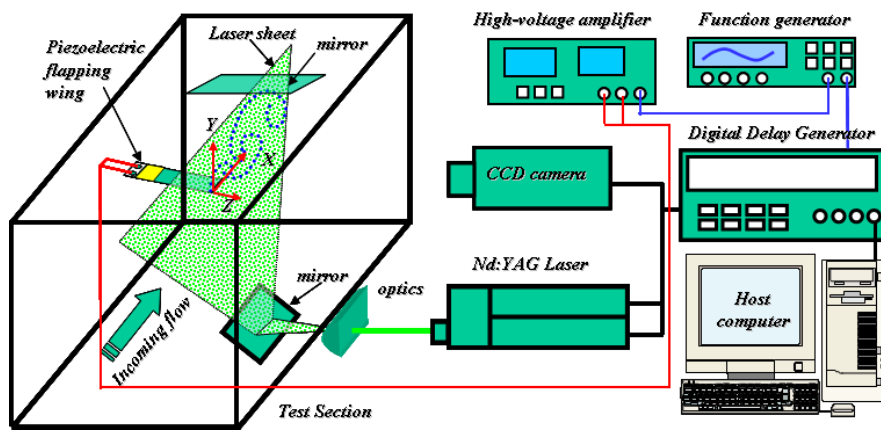
<sup>2</sup> Assistant Professor, Department of Electrical and Computer Engineering.

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**Fig. 1:** The studied piezoelectric flapping wing



**Fig. 2:** Experimental set up for PIV measurements

Figure 2 shows the experimental setup used in the present study. The test piezoelectric flapping wing was installed in the middle of the wind tunnel test section. A sinusoidal AC voltage, which was supplied by using a function generator and amplified through a high-voltage amplifier, was used to drive the piezoelectric flapping wing. The piezoelectric wing would be in plunging motion with the same frequency as the applied AC voltage. The amplitude of the plunging motion was found to reach its peak value when the frequency of the applied AC voltage matches the resonance frequency of the piezoelectric wing, which is 60 Hz for the present study. As shown in Figure 3, the peak-to-peak flapping amplitude of the wingtip was found to increase linearly with the applied AC voltage.

A digital PIV system was used in the present study to make detailed flow velocity field measurements to quantify the formation and separation processes of Leading Edge Vortex (LEV) structures on the upper and lower surface of the piezoelectric flapping wing in relation to the position of the wing during the up stroke and down stroke cycles as well as the evolution of the unsteady vortex structures in the wake of the piezoelectric flapping wing. The flow was seeded with 1~5  $\mu\text{m}$  oil droplets. Illumination was provided by a double-pulsed Nd:YAG laser (NewWave Gemini 200) adjusted on the second harmonic and emitting two pulses of 200 mJ at the wavelength of 532 nm with a repetition rate of 10 Hz. The laser beam was shaped to a sheet by a set of mirrors, spherical and cylindrical lenses. The thickness of the laser sheet in the measurement region is about 1.0 mm. As shown in Fig. 2, a mirror was installed on the top of the wind tunnel to reflect the illuminating laser sheet back to the measurement region to eliminate the shadow region of the piezoelectric flapping wing for PIV measurements. A high resolution 12-bit (1376 x 1040 pixel) CCD camera (SensiCam-QE, CookeCorp) was used for PIV image acquisition with the axis of the camera perpendicular to the laser sheet. The CCD camera and the double-pulsed Nd:YAG laser were

connected to a workstation (host computer) via a Digital Delay Generator (DDG, Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and image acquisition.

During the experiments, the sinusoidal wave signals supplied by the function generator, which was used to drive the piezoelectric flapping wing through a high-voltage amplifier, was also used as the input signal to the DDG to trig the PIV system to achieve phased-locked PIV measurements. By adding different time delays between the input sinusoidal wave signal and the TTL output signal from the DDG to trig the PIV system, the phased-locked PIV measurements at different phase angles (i.e., corresponding to different positions of the flapping wing) in the course of the upstroke and down stroke flapping motion of the piezoelectric flapping wing were accomplished. At each pre-selected phase angle, 160 frames of instantaneous PIV measurements were used to calculate averaged phase-locked flow field around the piezoelectric flapping wing. In addition to phase-locked PIV measurements, time-averaged PIV measurements were also conducted by disabling the phase-locking between the flapping motion of the piezoelectric flapping wing and the PIV system in order to derive the time-averaged flow field around the piezoelectric flapping wing. Instantaneous PIV velocity vectors were obtained from the acquired PIV images by using a frame to frame cross-correlation technique involving successive frames of patterns of particle images in an interrogation window  $32 \times 32$  pixels. An effective overlap of 50% of the interrogation windows was employed to derive instantaneous velocity vectors for the PIV image processing. After the instantaneous velocity vectors ( $u_i, v_i$ ) were determined, instantaneous spanwise vorticity ( $\omega_z$ ) could be derived. The time-averaged quantities such as mean velocity ( $U, V$ ), ensemble-averaged spanwise vorticity ( $\omega_z$ ) distributions were obtained from a cinema sequence of 500 frames of instantaneous velocity fields in each studied chordwise cross planes. The measurement uncertainty level for the instantaneous velocity vectors is estimated to be within 2.0%.

### III. Use Proper Orthogonal Decomposition method to analyze PIV data

The proper orthogonal decomposition (POD), also called the principal component analysis (PCA), or the Karhunen-Loeve (KL) decomposition, is a common technique to reduce a complicated flow behavior to a simpler one and to get the coherent structure of fluid flow. Essentially, the proper orthogonal decomposition uses the spatial or temporal correlation matrix to compute the eigenfunction, POD mode, and thus decompose the structures contained in the snapshots in the sense of energy. The POD modes can be used to simulate the weak flow by decrease the order of Navier-Stokes equation using Galerkin projection. POD method is optimal in the sense of energy. That is, using same number of modes, POD method captures more energy than any other model reduction method.

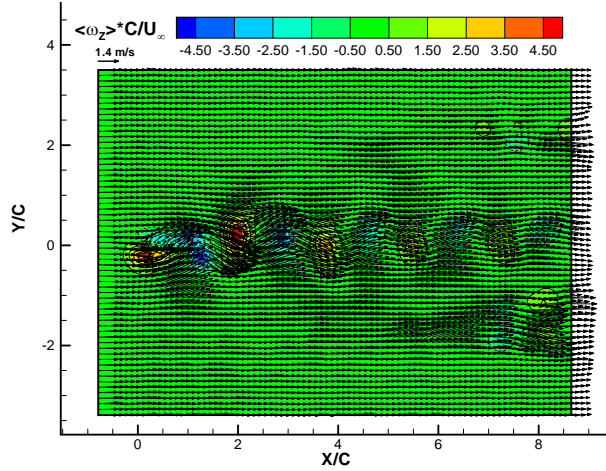
Since there are two different kinds of experimental data used, the synchronous data and non-synchronous data, one can obtain two different kinds of POD modes, synchronous POD mode generated from synchronous experimental data and the non-synchronous data generated from non-synchronous experimental data. We use the proper orthogonal decomposition method to analyze the data and hence to identify the coherent structure of weak flow of flapping wing.

When we use the snapshots to generate the POD modes, we need to figure out how many snapshots can be used in order to generate the POD mode containing full information in the sense that if we use more snapshots than current number of snapshots, the shape of vortex in the dominant POD modes (i.e. POD mode 1 and POD mode 2) will not change. In this section, we use 160 snapshots to generate POD modes in each case.

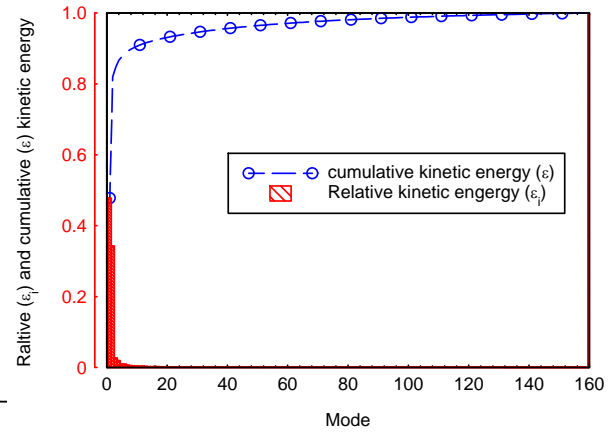
In each figure of this paper, we use different colours to characterize different vortex. The magnitude of the value of colorbar denote the curl value of vortex, and the sign of value of colorbar denotes the rotation direction of vortex. The negative values in the colorbar denotes that the rotation direction of vortex is clockwise and the positive values in the colorbar is used to indicate that the vortex is counter-clockwise.

#### POD modes of the PIV measurement results at different measured position

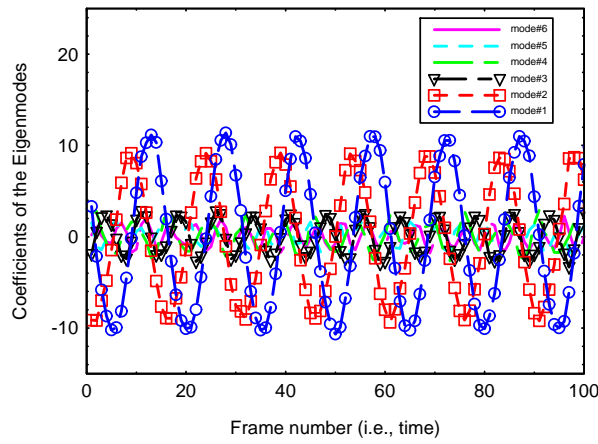
In Fig. 3 to Fig 11 should the pod analysis results of the PIV snapshots at different wingspan of the piezoelectric flapping wing (i.e., PIV measurement results in the plane passing 50% wingspan, 75% wingspan and wingtip)



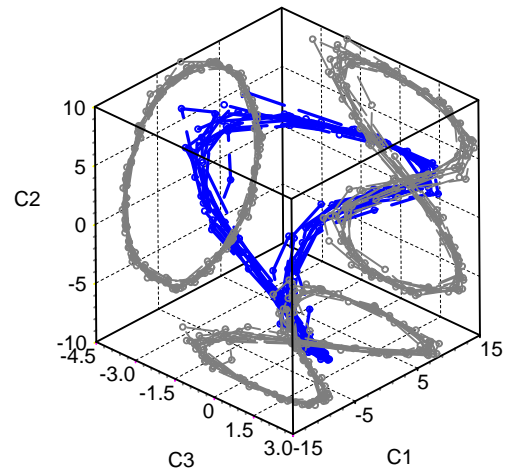
(a). a typical snapshot of the PIV measurement results



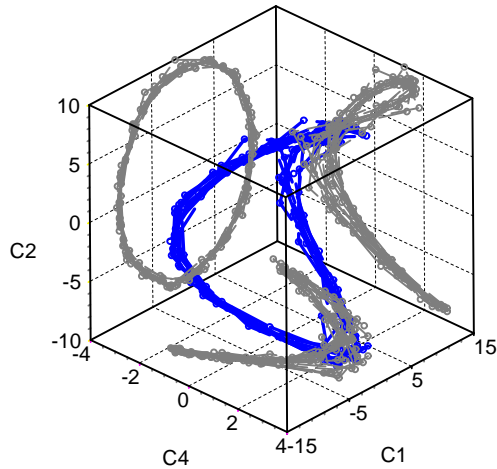
(b). Relative and cumulative kinetic energy of POD modes



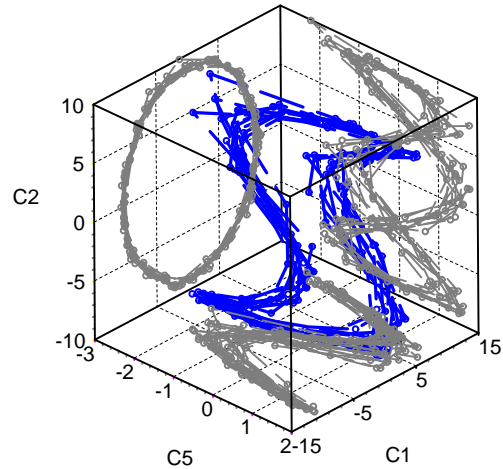
(c). Coefficients of the first 6 POD modes vs. frame number



(d). coefficients of POD mode #1, #2 and #3



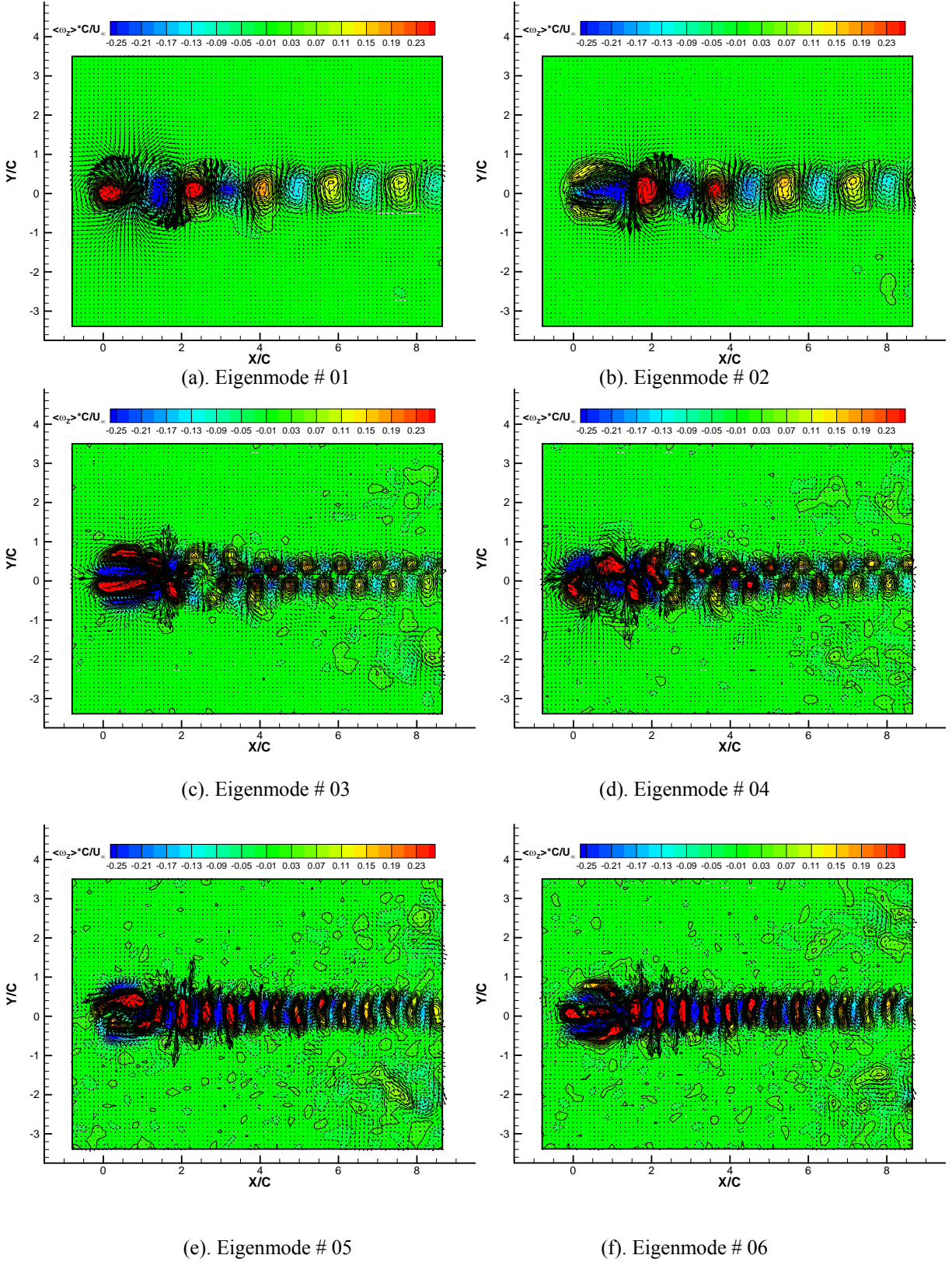
(e). Coefficients of POD mode #1, #2 and #4



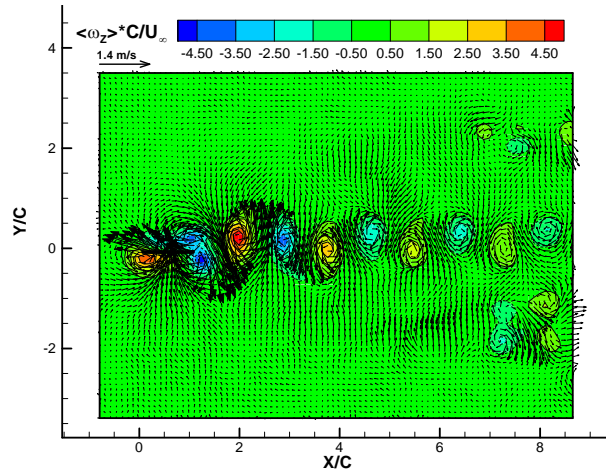
(f). Coefficients of POD mode #1, #2 and #5

**Fig.3:** POD analysis of the PIV measurement results at 50% wingspan

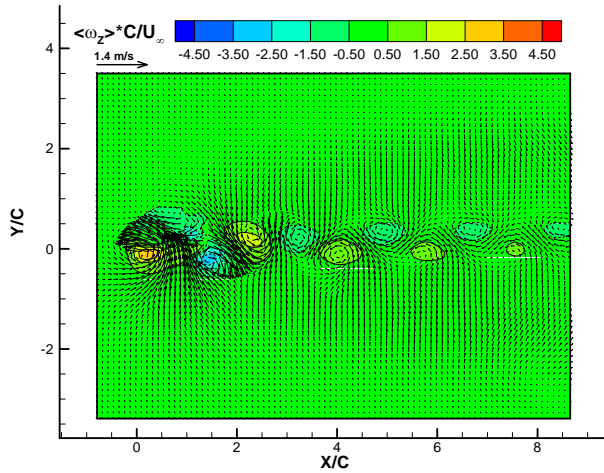




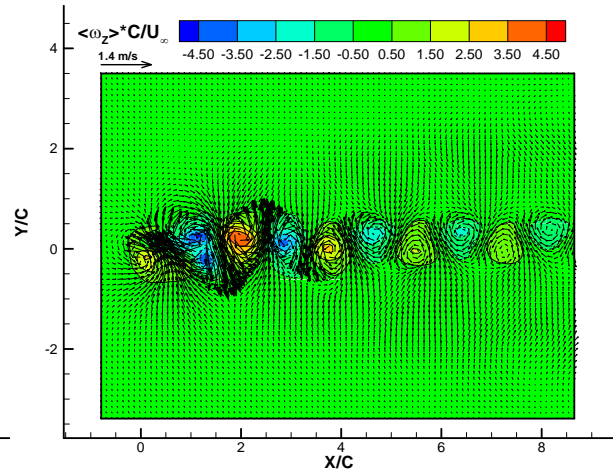
**Fig. 4:** the first 6 POD eigenmodes of the PIV measurement results in the plane at 50% wingspan



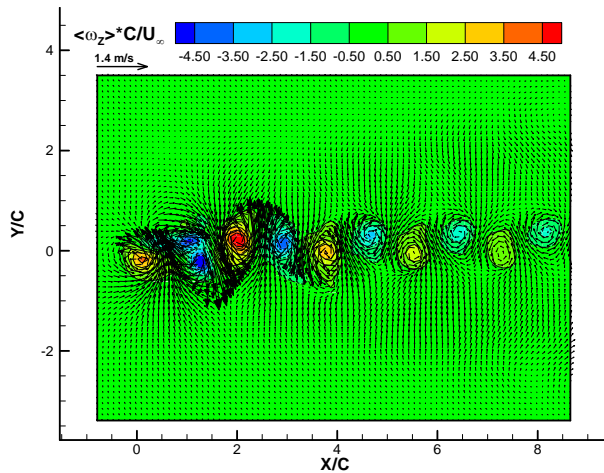
(a). original flow field



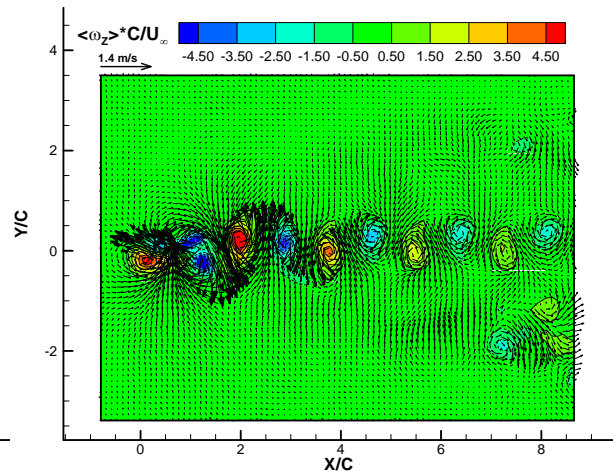
(b). using the first 1 modes (48% Kinetic Energy)



(c). using the first 2 modes ( 82% Kinetic Energy)



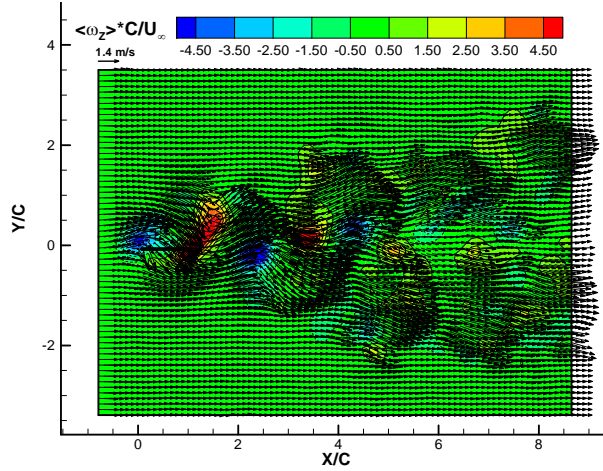
(d). using the first 5 modes (88% Kinetic Energy)



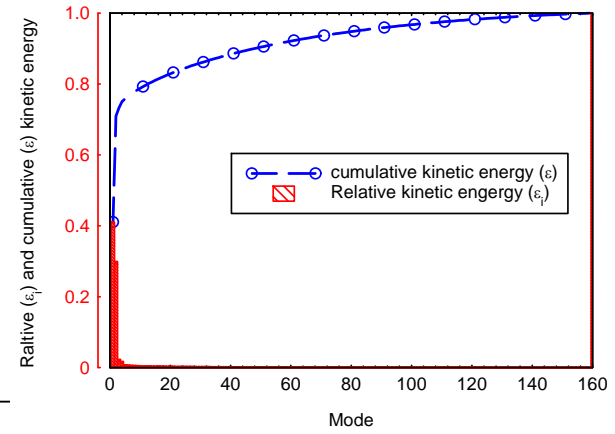
(e). using the first 50 modes ( 97% Kinetic Energy)

**Fig. 5:** Original flow field vs. the reconstructed flow fields using reduced POD modes @ 50% wing span

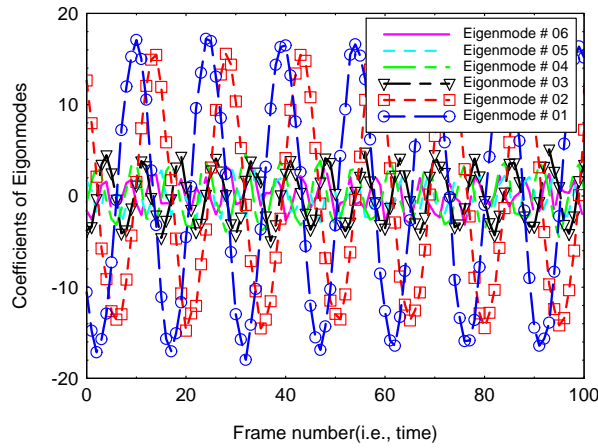




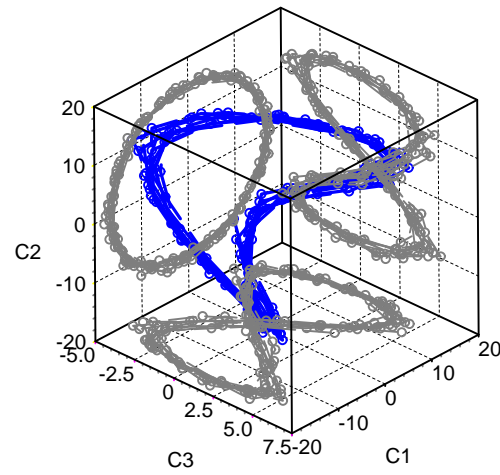
(a). a typical snapshot of the PIV measurement results



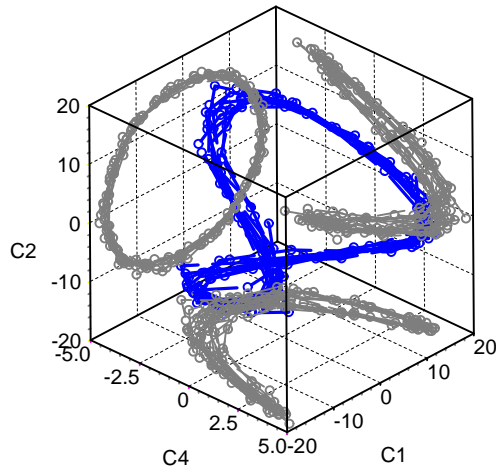
(b). Relative and cumulative kinetic energy of POD modes



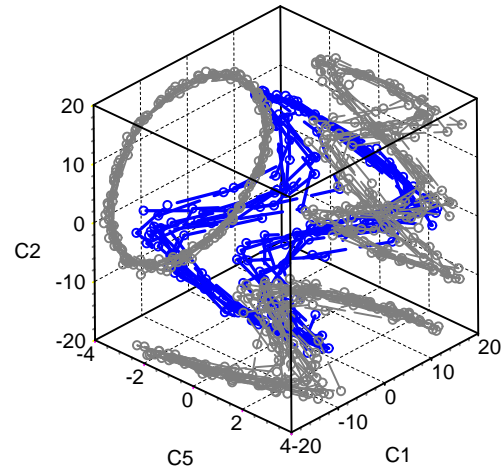
(c). Coefficients of the first 6 POD modes vs. frame number



(d). coefficients of POD mode #1, #2 and #3

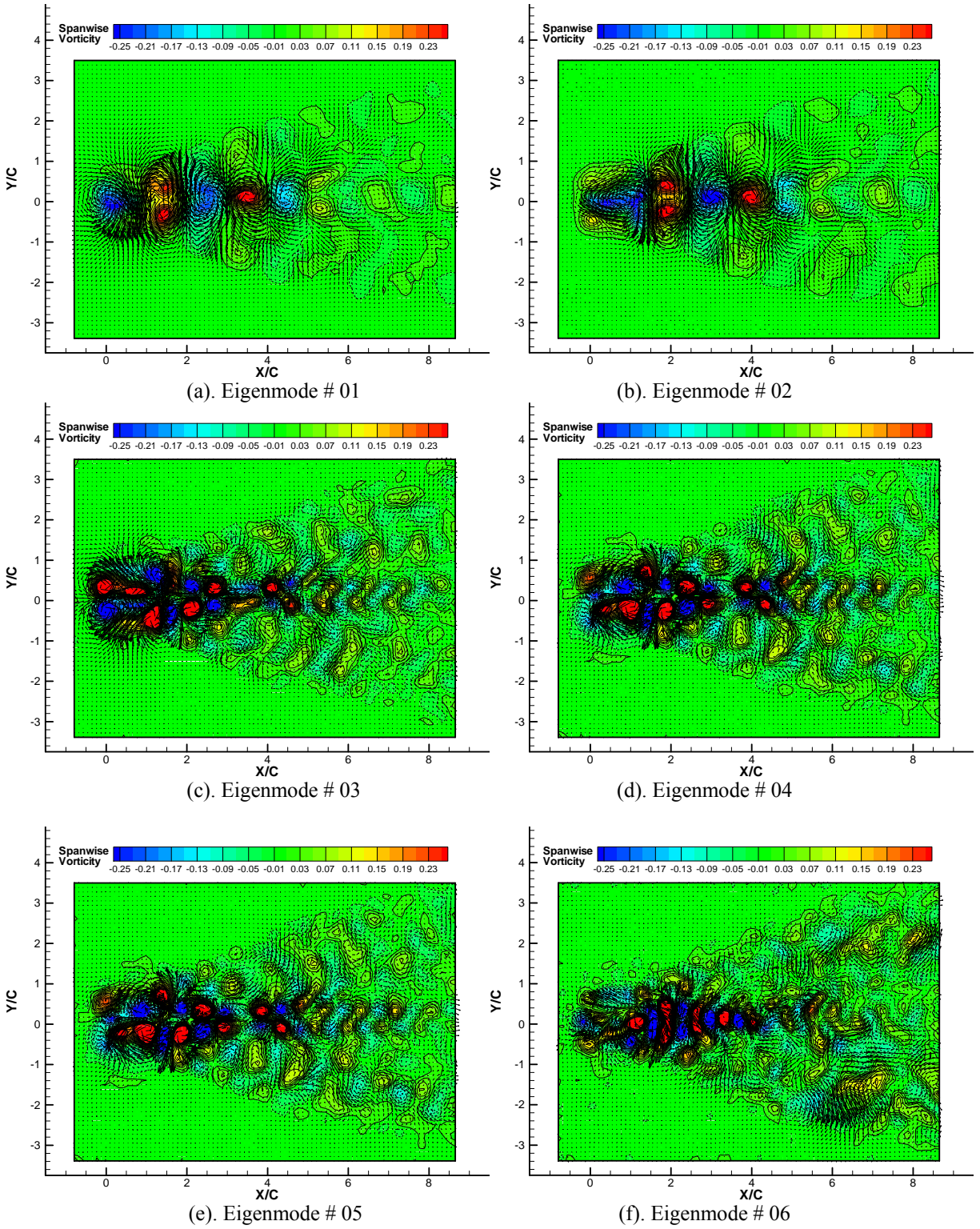


(e). Coefficients of POD mode #1, #2 and #4

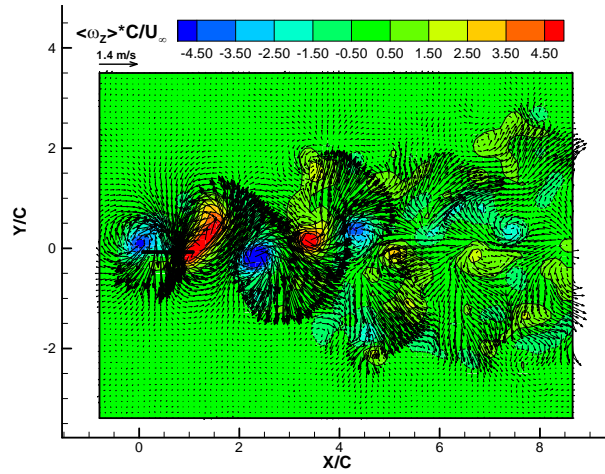


(f). Coefficients of POD mode #1, #2 and #5

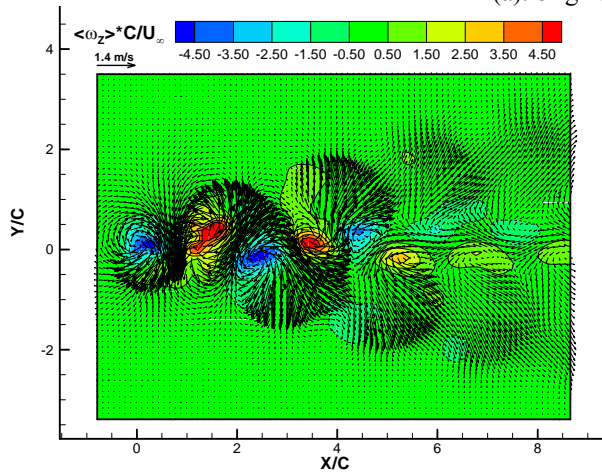
**Fig.6:** POD analysis of the PIV measurement results at 75% wingspan.



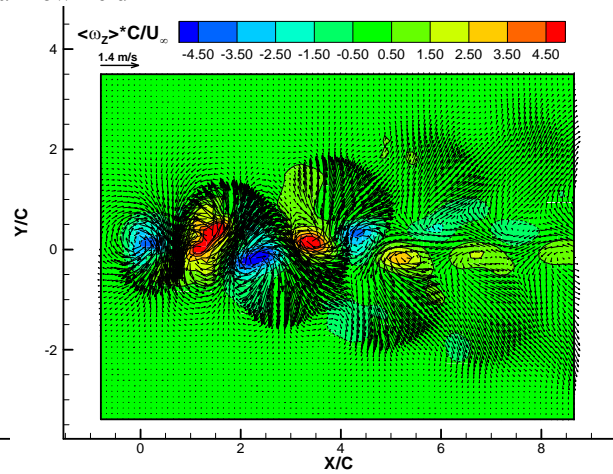
**Fig. 4:** the first 6 POD eigenmodes of the PIV measurement results in the plane at 75% wingspan.



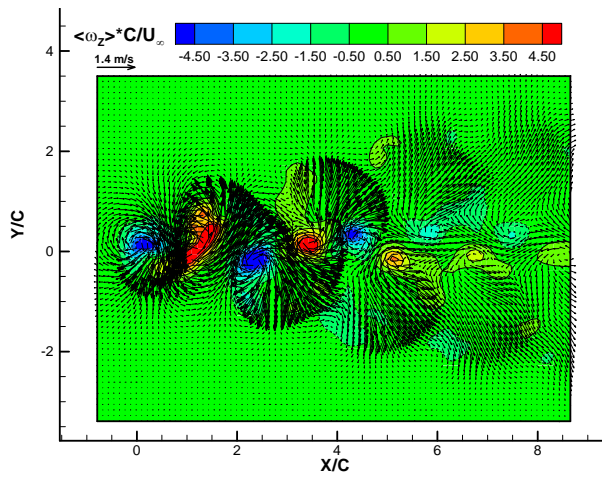
(a). original flow field



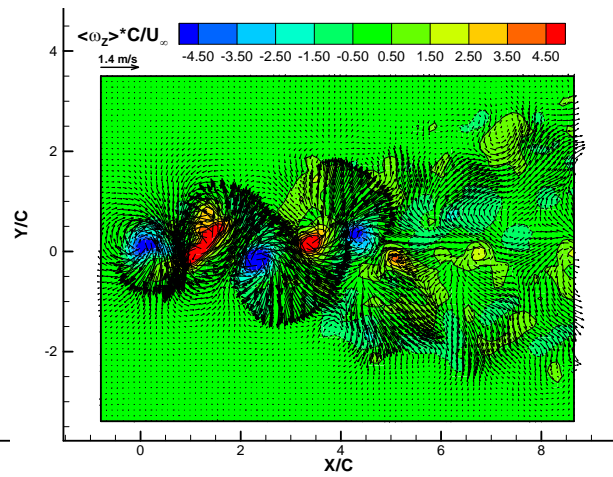
(b). using the first 1 modes (41% Kinetic Energy)



(c). using the first 2 modes ( 72% Kinetic Energy)



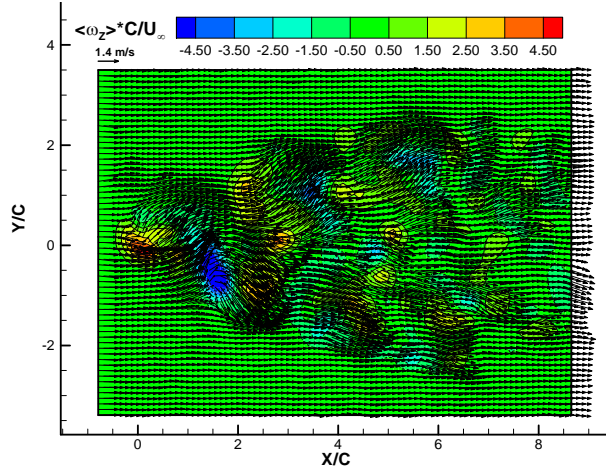
(d). using the first 5 modes (88% Kinetic Energy)



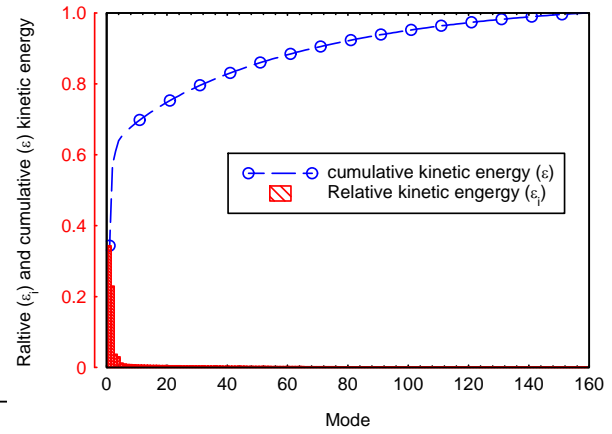
(e). using the first 50 modes ( 97% Kinetic Energy)

**Fig. 8:** Original flow field vs. the reconstructed flow fields using reduced POD modes @ 75% wing span

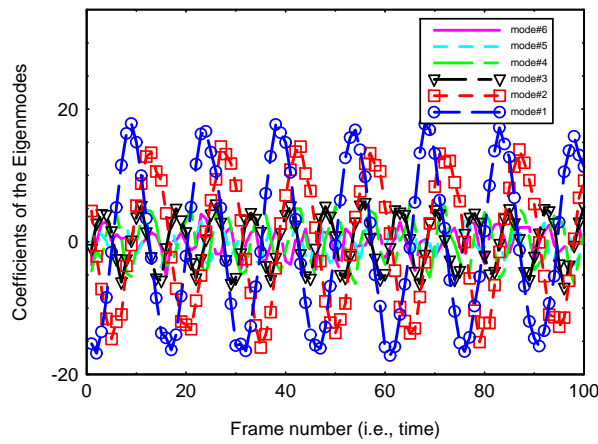




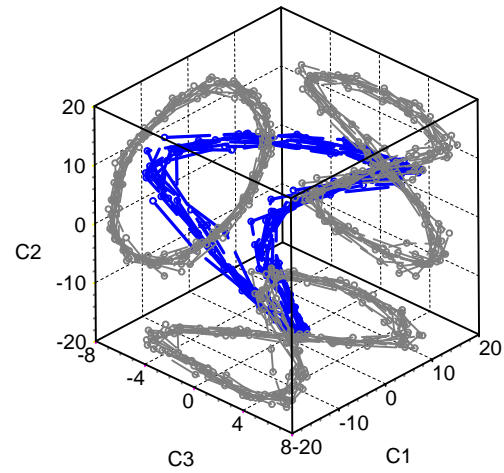
(a). a typical snapshot of the PIV measurement results



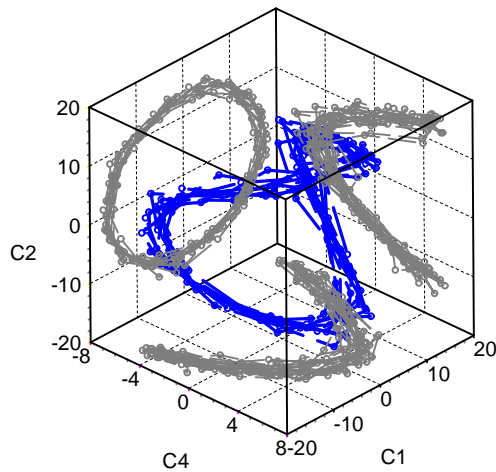
(b). Relative and cumulative kinetic energy of POD modes



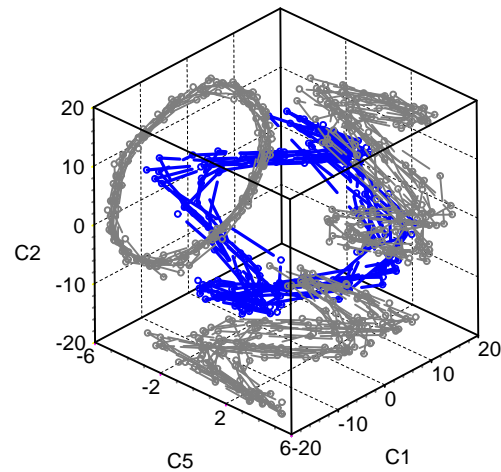
(c). Coefficients of the first 6 POD modes vs. frame number



(d). coefficients of POD mode #1, #2 and #3

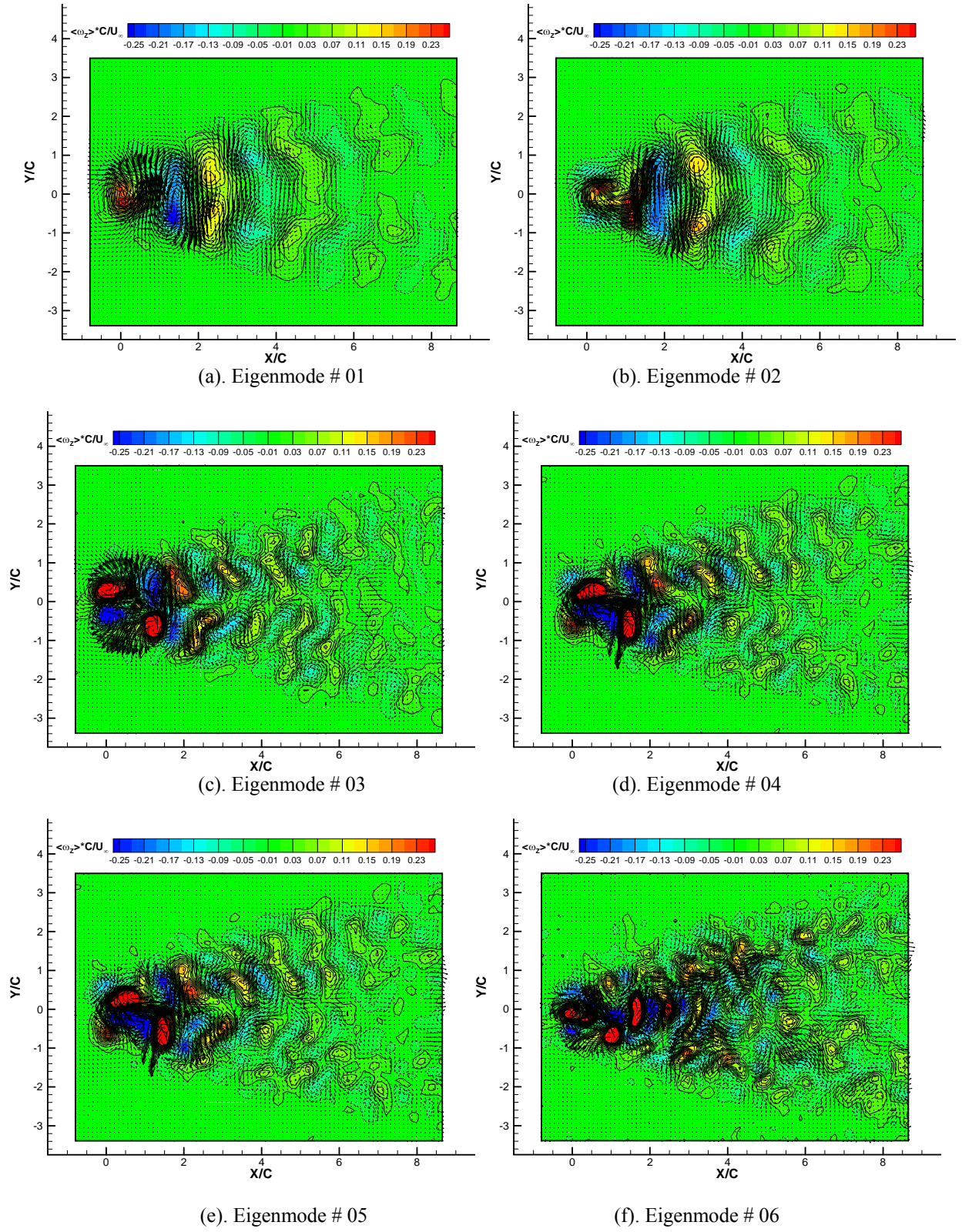


(e). Coefficients of POD mode #1, #2 and #4

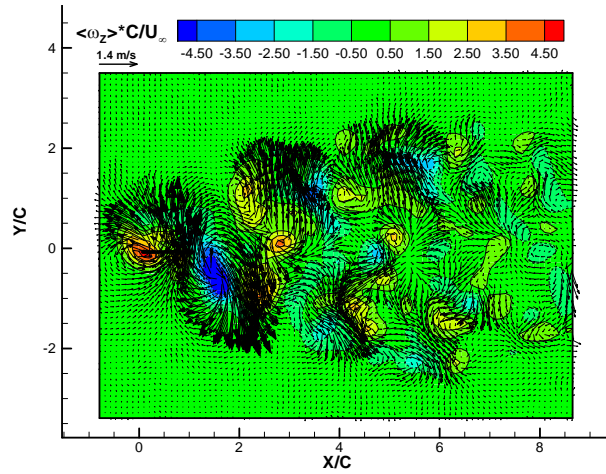


(f). Coefficients of POD mode #1, #2 and #5

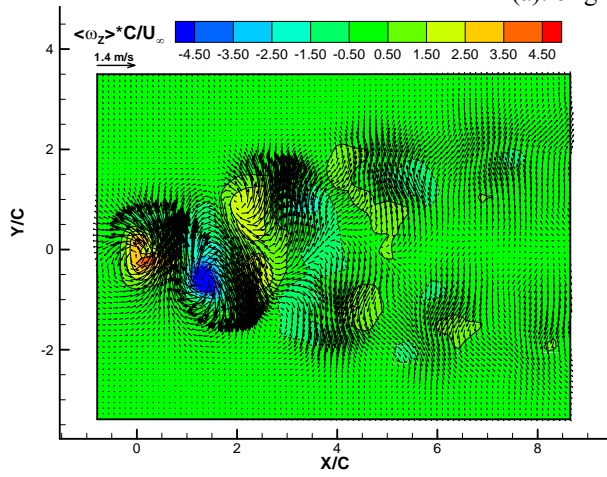
**Fig.9:** POD analysis of the PIV measurement results at wingtip.



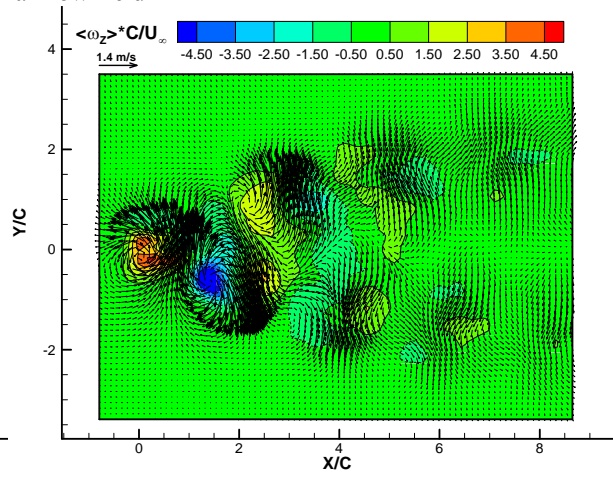
**Fig. 10:** the first 6 POD eigenmodes of the PIV measurement results in the plane at wingtip



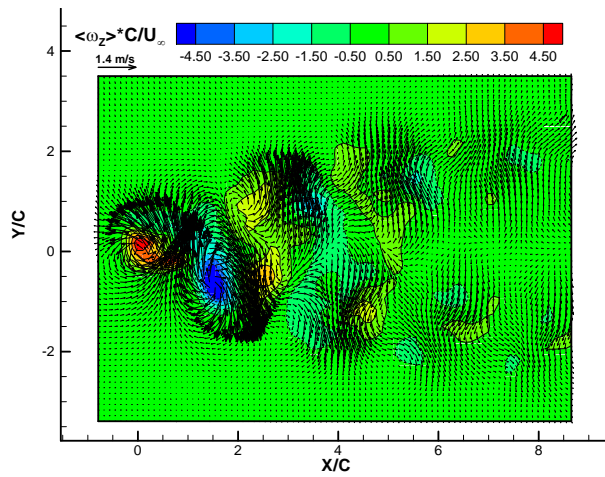
(a). original flow field



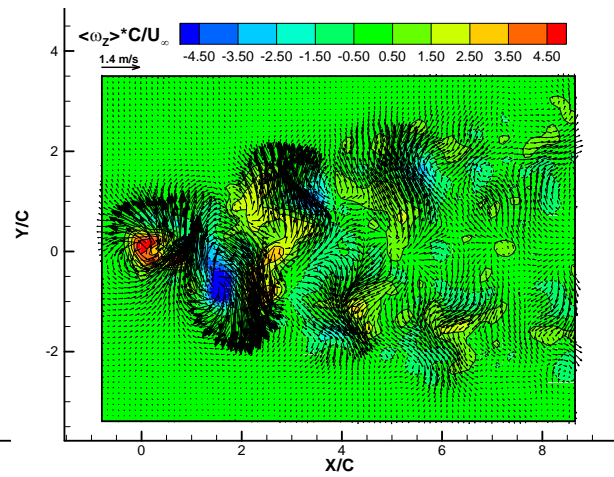
(b). using the first 1 modes (34% Kinetic Energy)



(c). using the first 2 modes ( 57% Kinetic Energy)



(d). using the first 5 modes (65% Kinetic Energy)



(e). using the first 50 modes ( 86% Kinetic Energy)

**Fig. 11:** Original flow field vs. the reconstructed flow fields using reduced POD modes @ wingtip